NASA-TM-86710

NASA Technical Memorandum 86710

NASA-TM-86710 19850018410

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NASA

National Aeronautics and
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N85-26721#

DEVELOPMENT AND FLIGHT TEST OF A HELICOPTER, X-BAND, PORTABLE PRECISION LANDING SYSTEM CONCEPT

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Abstract

A beacon landing system (BLS), based on a novel, X-band, precision approach concept is being developed and flight tested as a part of NASA's Rotorcraft All-Weather Operations Research Program. The system is based on state-of-the-art X-band radar technology and digital processing techniques. The BLS airborne hardware consists of an X-band receiver and a small microprocessor, installed in conjunction with the aircraft instrument landing system (ILS) receiver. The microprocessor analyzes the X-band, BLS pulses and outputs ILS-compatible localizer and glide slope signals. Range information is obtained using an on-board weather/mapping radar in conjunction with the BLS. The ground station is an inexpensive, portable unit; it weighs less than 70 lb and can be quickly deployed at a landing site. Results from the flight-test program show that the BLS has a significant potential for providing rotorcraft with low-cost, precision instrument approach capability in remote areas.

Introduction

A self-contained navigation system that could be set up with a minimum of ground-based equipment would permit full exploitation of the helicopter's unique capability to land in remote areas. In attempts to develop such a system, NASA Ames Research Center has been conducting research, originally with the University of Nevada, Reno, and currently with the Sierra Nevada Corporation of Reno, Nevada, to develop novel, X-band guidance systems for helicopter approaches and landings.

In the first phase of those efforts, the detection of passive ground-based corner reflectors using a device called an echo processor was successfully demonstrated.[1] Use of this passive-reflector detection scheme in an overland environment provides pilots with a target on their radar display, thus giving them the range and bearing information they need to make nonprecision airborne radar approaches.

To expand on the echo-processor technology, a second phase of the research program was undertaken with the objective of developing and demonstrating the feasibility of a weather-radar-based precision approach concept. The feasibility criteria for this concept included 1) minimal, passive, or battery-powered ground-based equipment; 2) minimal airborne modifications, requiring at most an easy retrofit to current radar-equipped civil rotorcraft; 3) piloting techniques similar to those used in making instrument landing system (ILS) approaches; and 4) precision approach tracking performance.

Initially, a design was pursued in which an array of directional passive reflectors oriented along the localizer track would provide the directional signals necessary to derive precision guidance. By using an on-board digital microprocessor installed in conjunction with the airborne weather radar, glide slope and localizer guidance would be calculated and displayed to the pilot on the existing ILS course deviation indicator (CDI). The reflector-based ground station would consist of at least five and preferably eight reflectors and would require no ground power. The spacing between reflectors would have to be longer than the typical 180 m (600 ft) pulse length of civil mapping radars. Therefore, the reflector-based ground station would require 1.2 to 2.1 km (4,000 to 7,000 ft) of terrain for installation. Although this requirement might not be a problem for aircraft landing on conventional runways, it would be impractical for heliports.

Presented at the 41st Annual National Forum of the American Helicopter Society, Ft. Worth, Texas, May 15-17, 1985.

As an alternative to the radar reflector array, a program was conducted in 1982 and 1983[2] in which an X-band transponder beacon with multiple-pulse-reply capability was modified to reply through an array of directional antennas (Fig. 1). The first-generation beacon-based ground station was packaged in an inexpensive, battery-powered portable unit. Localizer and glide slope information from the on-board microprocessor were hard-wired into the aircraft's CDI, and a cockpit switch was required for switching between beacon landing system (BLS) guidance and ILS guidance.

Although early testing of the BLS demonstrated its feasibility, the system had some undesirable features. For example, during BLS approaches the weather/mapping radar had to be switched to use a wide-coverage, nonscanning antenna instead of the normal 30 to 45 cm (12 to 18 in.) scanning antenna. Therefore, during approaches the radar was not available to the pilot for weather detection and obstacle avoidance. Also, the additional cockpit switch was considered undesirable because it increased the complexity of the aircraft modifications and created a potential for pilot error in selecting the proper switch position for ILS and BLS approaches. Early testing also established the need for antenna sizing studies, to eliminate multipath interference problems, and for localizer sensitivity studies, to eliminate pilot-induced directional oscillations at close ranges.

A fixed-base, piloted simulation was conducted to investigate pilot acceptability of several localizer "course-softening" algorithms. The simulation identified two promising algorithms that are being incorporated in the current, second-generation flight tests. In the first algorithm, when range information is available (i.e., when the BLS is installed in conjunction with a weather radar), the localizer deviation can be based on a constant-width coverage of ±350 ft for the last 8,000 ft of the approach. In the second algorithm, the angular coverage is increased from the initial ±2.5° to ±4°, and no range information is necessary. The FAA successfully flight tested this second algorithm for angular coverages of ±3° to ±4° for glide slopes of 3°, 6°, and 9° with a colocated microwave landing system (MLS).[3] Both of these algorithms are shown schematically in Fig. 2.

The current phase of the research program was designed to address the shortcomings disclosed in the early BLS work. With the current BLS equipment, full weather/mapping radar capability with a scanning antenna is preserved, and the only tie to the airborne-radar is to obtain range information. In aircraft that are not equipped with radar, localizer and glide slope course-deviation can be obtained, but range information would not be inherently available using BLS signals. An improved cockpit interface has been installed using existing ILS receivers. BLS guidance information is reformatted in an ILS-compatible format and is input to the airborne ILS receiver. Therefore, the pilot has no additional cockpit switches, and BLS approach procedures are nearly identical to ILS approaches. Other features of the current BLS include a more compact ground-station, improved resistance to multipath interference, and reduced localizer sensitivity at close ranges by use of localizer course-softening algorithms. This paper describes the BLS, provides a description of the second-generation system currently being tested, and presents the results of the flight evaluation.

Beacon Landing System Description

The BLS incorporates many of the principles that are used in a standard ILS. The BLS and ILS are both fixed-beam systems in which four directional beams are projected into space to provide localizer and glide slope information. Guidance in both systems is derived by beam-amplitude comparison. Operationally, both the BLS and ILS provide a single approach corridor, typically with the localizer course aligned with the runway and with a 3° glide slope.

The major differences between the BLS and an ILS are the carrier frequency, glide slope beam projection technique, and beam-discrimination methods. First, the carrier frequency for an ILS is two orders of magnitude lower than for the X-band BLS. Since antenna size to achieve a given beam width is inversely proportional to carrier frequency, the high frequency of the BLS makes it possible to use small antennas at the ground site. Second, an ILS uses a ground bounce technique to project the glide slope beams into space, while BLS requires no ground bounce but projects the glide slope beams directly into space. Third, the techniques for discriminating between the four beams are very different. For an ILS, the ground signals are transmitted on a continuous wave (CW) basis, and they are tone-modulated for purposes of discriminating between the beams. The BLS makes use of the multiple-pulse transmission capability of X-band transponder beacons, incorporating a high-speed switching circuit to transmit the time-sequenced pulses through directional antennas. The on-board microprocessor can then discriminate between the directional guidance beams based on the time sequencing of the pulses.

The BLS has several unique attributes which would be useful for many civil and military

rotorcraft missions. To attain a comparable beamwidth, an ILS localizer antenna must be 85 times wider than a BLS localizer antenna, and an ILS glide slope antenna must be 14 times taller than a BLS glide slope antenna. The BLS can operate in a transponder mode in which the range to the ground station is inherently available for radar-equipped aircraft. Other landing systems (BLS too when used by aircraft not equipped with radar) require colocated distance-measuring equipment (DME) or marker beacons to provide the pilot with range fixes. Also, because the BLS does not require ground bounce for the glide slope beams, it also does not require any surface preparation in front of the glide slope antenna. This makes the BLS well suited for landing sites where surface preparation would be impossible. Additionally, the BLS pulse-type transmissions require less power than the ILS continuous-wave transmissions. Because of the narrow guidance beams and the short guidance pulses, the BLS has demonstrated resistance to multipath interference. Also, inherent in the pulsed-type system is a high resistance to signal jamming.

The BLS operates on the principle of four overlapping, narrow, X-band beams transmitted from highly directional antennas and oriented left, right, above, and below the desired flightpath. The sketch in Fig. 3 depicts the two beams that form the glide slope, one above and one below the desired flightpath. With this beam orientation, as the aircraft deviates from the desired glide slope, one signal increases in amplitude and the other decreases. When both signals are of equal intensity, the aircraft is on the glide slope. Glide slope deviation from the desired course is proportional to the difference in received signal strength of the up-down beams. Localizer deviation is similarly derived using highly directional left-right beams. False-course suppression is provided by two sector antennas oriented left and right of course. The BLS airborne processor compares the amplitude of the signals transmitted from the sector antennas with the signals transmitted from the highly directional antennas and rejects signals of lower amplitudes than those of the sector antennas. This eliminates false courses generated by beam side lobes. A more complete description of the ground and airborne systems follows.

Ground-Based System

The BLS ground station has only a few components. It consists of an X-band radar transponder beacon, two microwave switches and their associated control logic circuitry, an antenna array, and a 24 Vdc battery.

In a standard beacon, a group of time-sequenced pulses is transmitted through an omnidirectional beacon. The first pulse of the group identifies the beacon position, and the additional replies are used for identification. In the BLS, the beacon is modified so that upon interrogation by an airborne weather radar, the first reply pulses from the beacon are transmitted through the omnidirectional antenna, thus providing a wide-coverage reply for landing-site position and identification. This information is sufficient to provide the pilot with a conventional, nonprecision airborne-radar approach capability. Following the omnidirectional pulses, eight additional pulses are sequentially transmitted through, respectively, the left-sector antenna, the up and down precision antennas, the right-sector antenna, the left-sector antenna (again), the left and right precision antennas, and, finally, the right-sector antenna (again). In the absence of an interrogation signal from an airborne weather radar, the beacon squitters transmissions through the six directional antennas at a rate of 100 pulse trains per second. While in this squitter, or asynchronous, mode, the aircraft can receive localizer and glide slope guidance, but no range information can be derived. This asynchronous mode makes it possible for an aircraft without a weather radar to make a precision approach using the BLS.

These beacon transmission modes are controlled by adding two switch-control logic circuits. The first logic circuit is used to control a single-pole, two-throw, solid-state microwave switch. In the normal mode, this switch is in position 2, which allows the asynchronous mode of operation. Upon an interrogation, this switch goes to position 1, which results in a sequential transmission of beacon reply pulses through an omnidirectional antenna for position and identification and for subsequent transmission of beacon pulses through the second logic circuit. This second logic circuit controls a single-pole, six-throw, solid-state microwave switch. This switch allows sequential transmission of the eight beacon pulses through the six directional antennas.

As seen in Fig. 1, the four directional antennas used for the first-generation BLS ground station were standard 30 cm (12 in.) weather-radar, flat-plate antennas. Those antennas were chosen for test purposes because of their low cost and availability, but testing revealed multipath problems associated with such small antennas. A study of antenna size versus system performance indicated that BLS antennas 60 to 120 cm (2 to 4 ft) in height would be best.

The second-generation BLS ground station (Fig. 4) contains two dual-lobe parabolic antennas

and two sector antennas. The parabolic antennas are 20 cm (8 in.) wide, 69 cm (27 in.) high, and have focal-length-to-height ratios of 0.26; the two sector antennas are 8 cm (3 in.) wide and 51 cm (24 in.) high. Each parabolic antenna contains two appropriately oriented feed horns so that one antenna provides the left and right beams for localizer guidance, and the other provides the up and down beams. These antennas have a 3.3° vertical beamwidth and an 11° horizontal beamwidth. The left-right antennas are aimed ±6.5° from the localizer centerline and are 4 dB down from peak gain when on the localizer course. The up-down antennas are aimed ±1.9° from the desired glide slope and are 4 dB down from peak gain when on glide slope. These antennas allow for BLS operations at glide slopes of 4° or greater. The sector antennas provide false-course suppression in addition to proper localizer CDI indications up to ±35° from the course centerline. These antennas have been modified to decrease the vertical aperture to 23 cm (9 in.) and have a 6° vertical beamwidth, a 60° horizontal beamwidth, and are aimed ±30° left and right of the localizer course (Fig. 5). Since the peak gain of the sector antennas is considerably less than that of the precision guidance antennas, transmitted power from the precision antennas has been attenuated by 9 dB.

This antenna arrangement provides precision, linear left-right guidance at angles up to ±5° from localizer centerline, and sector-derived coarse guidance for full-scale fly-left/fly-right cockpit indications is available ±35° from localizer centerline. Deviations greater than ±35° from centerline result in off-flags.

The current ground station, incorporating the two parabolic antennas, the two sector antennas, and the omnidirectional antenna, is packaged in a compact, portable, composite enclosure (Fig. 4). This ground station weighs less than 70 lb (including a 10 lb battery), is 85 cm (33.5 in.) wide, 76 cm (30 in.) high, and 39 cm (15.5 in.) deep. It requires 30 W (1.2 A at 24 Vdc) of power, and can be set up by one person in less than 10 minutes. The tripod support legs make it easy to level and align.

Airborne System

The BLS airborne equipment (Fig. 6) comprises a small X-band antenna, an X-band receiver, and a processor. It uses 15 W of 28 Vdc input power, and the BLS equipment is easily interfaced with on-board avionics. The X-band antenna is a small waveguide/horn antenna 2.7 cm (1.06 in.) wide, 3.2 cm (1.25 in.) high, and 5 cm (2 in.) deep. The antenna is interfaced directly into the 400 cm^3 (24 $in.^3$) X-band receiver, and both are mounted in the aircraft's radome; the receiver bandwidth is 20 MHz. The processor uses a 16-bit digital microprocessor with analog to digital (A/D) and D/A converters. The processor analyzes the received X-band video signal to calculate range, localizer and glide slope deviation, and automatic gain control (AGC) for the receiver. The weather-radar modulator trigger is input to the BLS processor for range determination when the BLS is in its synchronous (transponder) mode. If using the airborne weather radar, range is available by noting the position of the beacon return on the weather-radar display. Range can also be displayed on a panel-mounted digital display. The localizer and glide slope signals are output from the processor in ILS-format, tone-modulated signals on 108.1 MHz for localizer and on 334.7 MHz for glide slope. These ILS-format signals are input to the localizer and glide slope antenna lines using BNC "T" connections. The pilot simply tunes his ILS receiver to the correct frequency (108.1 MHz) and the information is available on the CDI or used by the flight director or autopilot when the approach mode is engaged.

There are two versions of the processor: 1) a 13,000 cm^3 (800 $in.^3$) version, which contains high-accuracy range-calculation circuitry and additional D/A's for analog data output; and 2) a smaller, 1,500 cm^3 (90 $in.^3$) version, which does not, however, calculate range as accurately. A production version with high-accuracy range-calculation capability is expected to have a volume of less than 1,000 cm^3 (60 $in.^3$) and to weigh less than 1.8 kg (4 lb).

System Operation

Figure 7 shows a schematic trace of the eight BLS guidance pulses. The first set of four pulses is for the glide slope; those pulses are spaced at 6-μsec intervals. The second set of four pulses is for the localizer; the first three pulses are spaced at 6-μsec intervals and the last one at a 9-μsec interval. The BLS microprocessor is programmed to search for the two sector-antenna pulses that are 18-μsec apart and to identify them as glide slope framing pulses; similarly, it is programmed to search for the two sector-antenna pulses that are 21-μsec apart and to identify them as localizer framing pulses. When consistent sector-antenna returns are received, the largest of the four pulses is used to adjust the AGC voltage, keeping the X-band receiver in its linear range and ensuring that side lobes of the directional precision-guidance antennas do not generate false courses. For each pair of guidance signals, the signal amplitudes are differenced, scaled, and filtered for output to the ILS formatting circuit in the BLS processor.

With the current BLS dual-mode equipment, the ground station automatically switches between the synchronous (transponder) and asynchronous modes. The airborne radar, sweeping a ±30° sector at a sweep rate of 24°/sec, interrogates the BLS ground station for about 0.3 sec of each 2.5-sec period. Between these periods of synchronous operation, the BLS reverts to the asynchronous mode of operation to provide continuous localizer and glide slope deviation information. Range updates are only obtained while the ground station is in the synchronous reply mode.

Flight-Test Program

Initial flight tests of the BLS demonstrated the system's ability to achieve precision approach tracking, and provided a survey of pilot opinions of system performance.[2] Current BLS flight testing, using the second-generation equipment, has the following objectives: to demonstrate and test simultaneous weather radar and BLS operation and investigate possible interference between the two systems; to obtain pilot comments on the operational suitability of the ILS output module; to demonstrate improved resistance to multipath interference; and to obtain pilot comments on algorithms designed to reduce localizer sensitivity at close ranges. Maximum range and operationally feasible glide slopes were also determined. Simultaneous weather radar and BLS operation was demonstrated during many of the flights, and BLS operation in the presence of X-band tracking radars at Crows Landing (Calif.) was tested during several flights. Operational suitability of the ILS output module was evaluated on the basis of pilot comments. Resistance to multipath interference was tested by conducting flight tests at locations considered susceptible to multipath. Localizer course-softening algorithms are currently being flight tested, and data are being gathered on pilot evaluations and pilot tracking performance.

Aircraft

The test aircraft is an instrument-flight-rules (IFR) equipped Sikorsky SH-3G helicopter (Fig. 8), the military equivalent of the S-61N. The SH-3G is a twin-turbine, five-bladed, single-rotor helicopter with emergency amphibious capabilities. The aircraft has a flying-boat hull and two outrigger sponsons; the main landing wheels retract into the sponsons. The rotor diameter is 19 m (62 ft), the gross weight is 8,660 kg (19,100 lb), and the maximum airspeed is 120 knots. During flight testing, two pilots, the aircraft crew chief, and one to four experimenters were aboard. Experimental equipment and data-acquisition system equipment were mounted on a rack in the cargo area.

Test Locations

The SH-3G helicopter is based at Ames Research Center. System checkout and initial evaluation flights were made at Moffett Field, and quantitative data-collection flights were made at the NASA Ames Flight Systems Research Facility at Crows Landing, Patterson, California. Radar tracking systems, a data telemetry receiver, and ground-based data monitoring and recording equipment, were used to record quantitative data to analyze BLS performance. In addition to these locations, BLS approaches were made to small civil airports and remote-site helipads.

The approach procedures being tested are similar to those used for standard ILS approaches. Conventional enroute navigation aids (such as VOR/DME, TACAN, LORAN, NDB, and weather radar) were used to position the aircraft for BLS intercept. Following acquisition of the BLS guidance, the warning flags on the ILS course-deviation indicator disappear, and the pilot intercepts and tracks inbound on the BLS course.

Flight-Test Results

Figure 9 shows a typical view of the helicopter during testing as it approaches the battery-powered BLS ground station on an approach. Testing to date with the second-generation equipment has demonstrated BLS guidance intercept at ranges out to 24 km (17 n. mi.) and glide slopes ranging from 4° to 9°.

Early testing with the BLS equipment has confirmed its ability to operate in high radar noise environments. In flight tests, the BLS and airborne weather radar have been operated concurrently, and neither system affects the normal operation of the other. Bench testing with the airborne equipment has been conducted with up to 10,000 noise pulses per second injected into the received X-band signal. During flight tests, the X-band tracking radars at Crows Landing produce 2,000 pulses per second of noise, and the airborne weather radar provides an additional 120 pulses per second. In the presence of these noise pulses, BLS performance is normal, confirming its resistance to interference and jamming.

The ILS-compatible output format has also performed very well, and pilot response to this method of interfacing the BLS with the aircraft systems has been very positive. Since the BLS guidance is displayed on the normal ILS instruments, ILS and BLS approaches are virtually indistinguishable. Use of this ILS output format has

also allowed fully coupled autopilot approaches to the BLS, and no wires were cut to install the equipment. Pilots have been particularly impressed because no cockpit switches were added and no additional training was required to make BLS approaches.

The BLS has also demonstrated considerable resistance to multipath interference. During early testing of the BLS, a localizer course wander was noted below the glide slope at close range. Further investigation identified multipath problems from mismatched localizer beam side lobes. A minor modification to the localizer antenna corrected the problem. Many of the BLS approaches were made at locations susceptible to multipath interference. These locations included South Lake Tahoe, California, an access road at Crows Landing next to a dirt embankment, and Moffett Field, where large hangars are present on both sides of the runway. Traces of the BLS guidance signals were recorded on a strip chart and no oscillations in the signals were found, thus confirming the resistance of the BLS to multipath interference. Also, pilot evaluations of the BLS at these locations point out the absence of course bends, wiggles, and other undesirable characteristics normally attributable to multipath interference.

Reduced localizer sensitivity at close range is achieved by using localizer course-softening algorithms. Current flight tests are being used to evaluate two of these algorithms which were described earlier. Preliminary results show that by increasing the angular coverage from ±2.5° to ±4°, pilot acceptability is increased and precision approach tracking performance is maintained.

Alternative System Configurations

During the course of the BLS research program, alternative system configurations were devised using the BLS guidance principles, and those configurations demonstrate the flexibility of the BLS design. First, split-site localizer and glide slope ground stations were developed and are currently being demonstrated for typical runway operations. The two stations transmit asynchronously, and operation has been demonstrated with station separation ranging from 0 to 2.75 km (9,000 ft). Second, a configuration incorporating a DME or TACAN ground station along with the BLS ground station could have wide applicability. This configuration would allow DME-equipped aircraft to obtain range information without an airborne radar and allow for channelization by synchronizing BLS guidance pulses with the DME pulses. Lastly, flight tests have been performed using glide slopes as shallow as 2.5°, by using ground-station antennas 99 cm (39 in.) high instead of the 69 cm (27 in.) high antennas used in the current BLS ground station. Use of the taller antennas could be particularly useful where both rotorcraft and fixed-wing aircraft share the BLS-served facility.

Conclusions

A novel X-band, precision approach guidance system was successfully developed, and the concept feasibility was demonstrated in flight testing. The beacon landing system appears to have significant potential for both civil rotorcraft operations and certain military missions in which remote-site precision landing systems are required. The portability and low power consumption of the BLS ground station are also attractive for emergency and rapid-deployment missions that require precision approach capability. Specific project conclusions are as follows:

1) Using the BLS concepts, a portable, compact, inexpensive, lightweight, and battery-powered ground station can be designed.

2) ILS-type guidance can be derived using a small X-band receiver and a small microprocessor, both of which are easily interfaced with the aircraft's existing avionics.

3) Pilot workload and techniques for BLS approaches are similar to those in conventional ILS approaches.

4) BLS is resistant to interference from other X-band signals. Also, concurrent airborne weather-radar and BLS operation demonstrated that the systems do not interfere with each other.

5) Input of BLS guidance signals to the aircraft's ILS receiver provided a suitable, yet simple, way of interfacing with pilot displays and aircraft autopilots.

6) Use of 69 cm (27 in.) high parabolic antennas allows for multipath resistant operation at glide slopes of 4° or greater.

7) For colocated localizer and glide slope installations, simulation results show that pilot workload at close ranges can be reduced by using an on-board algorithm for localizer course softening.

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[2]Clary, George R. and Chisholm, John P., "Development of an X-Band Precision Approach Concept for Remote Area Rotorcraft Operations," Paper No. 88, IEEE/AIAA 5th Digital Avionics Systems Conference, Seattle, Wash., Nov. 1983.

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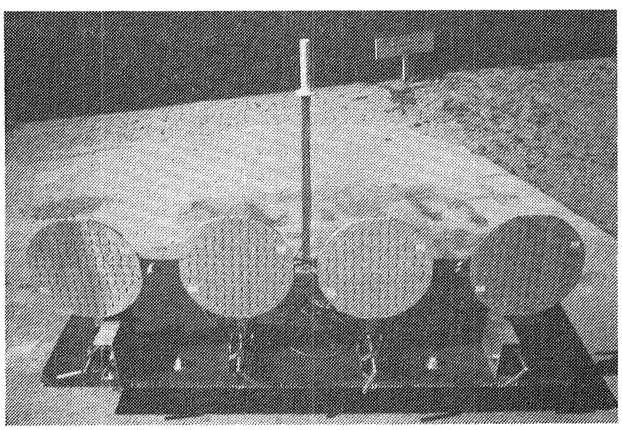

Fig. 1 First-generation BLS ground station.

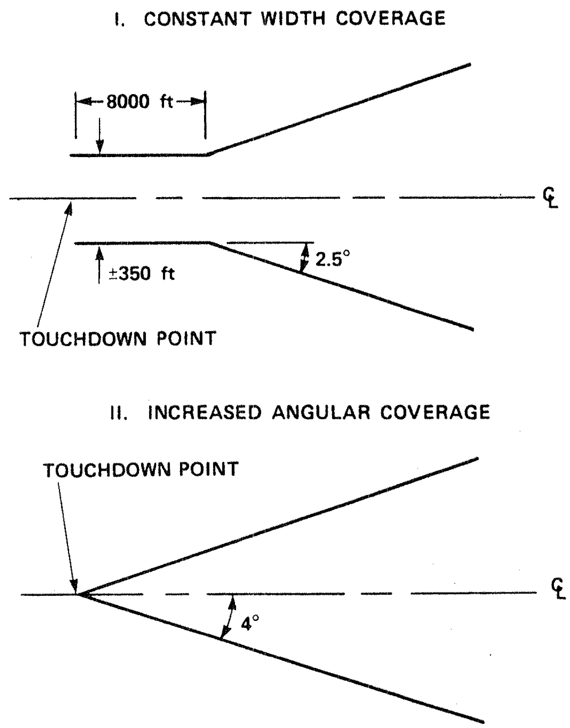

Fig. 2 Course-softening algorithms. 1) Constant width coverage; 2) increased angular coverage.

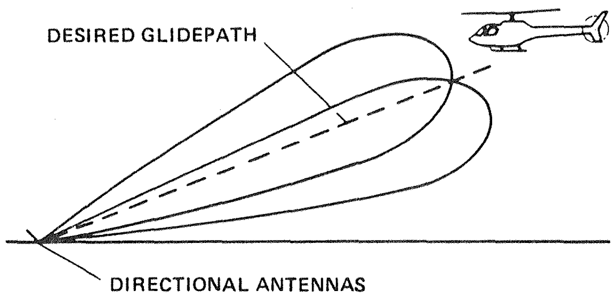

Fig. 3 Overlapping directional antenna beams provide course guidance.

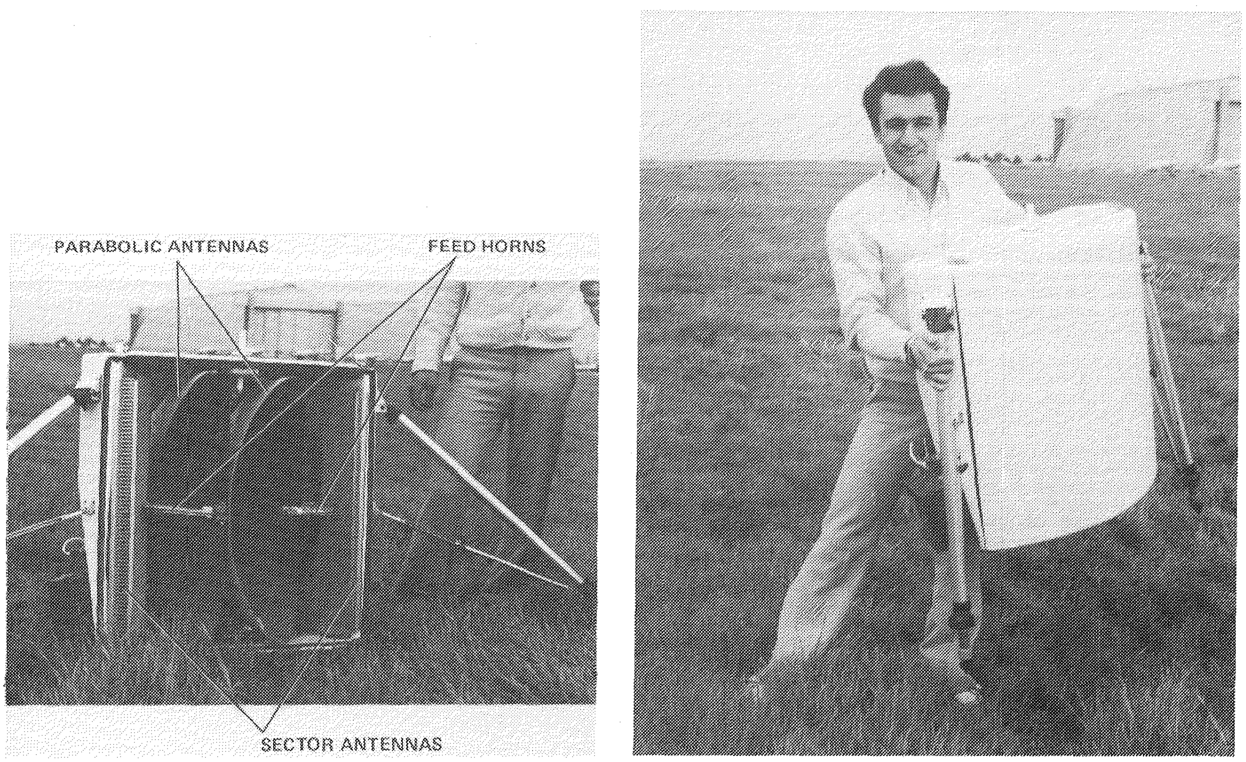

Fig. 4 Second-generation BLS ground equipment.

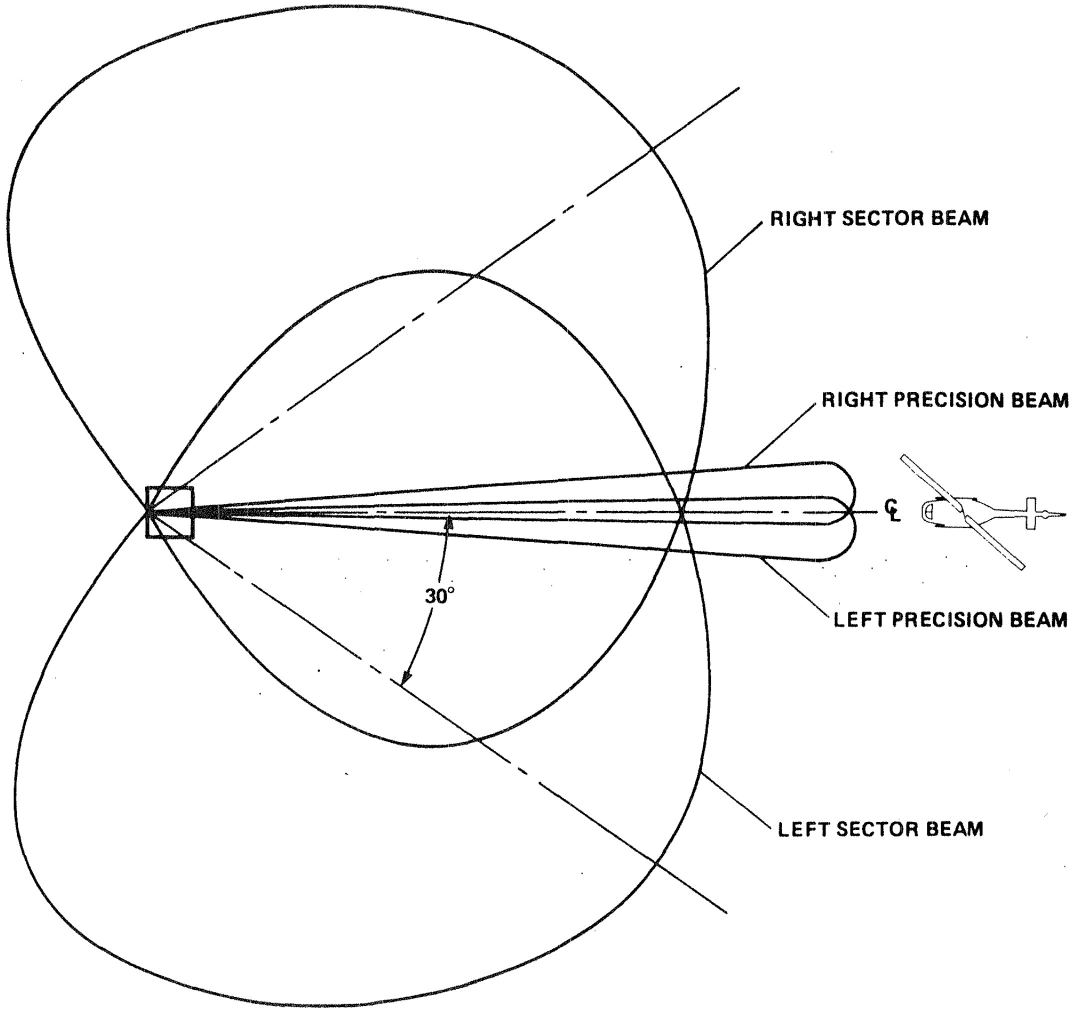

Fig. 5 BLS localizer beam configuration.

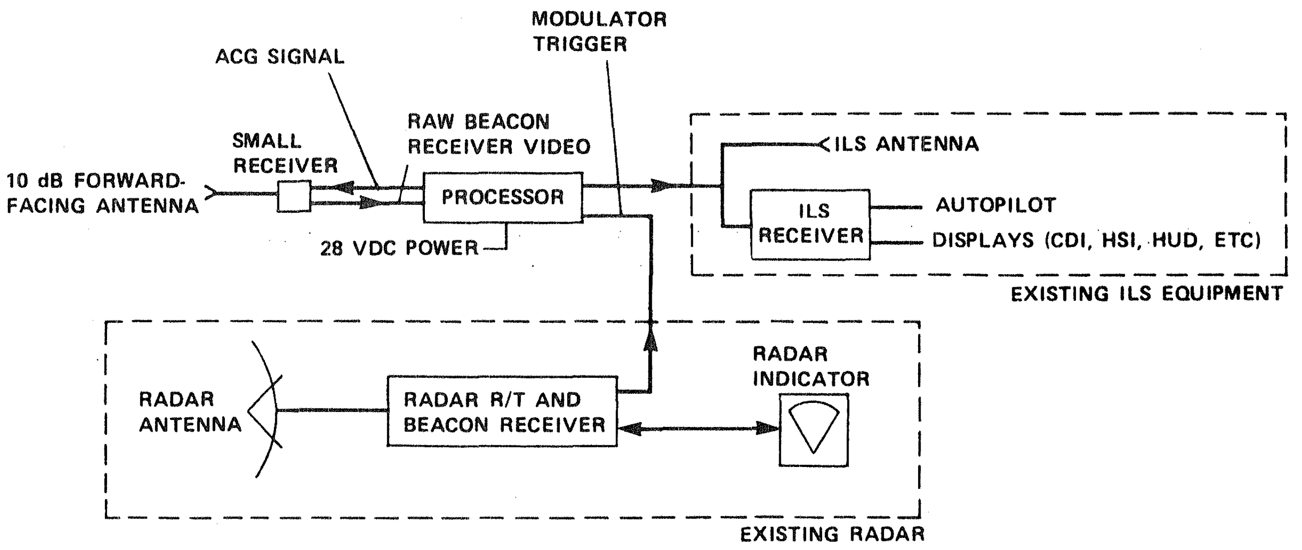

Fig. 6 BLS airborne equipment.

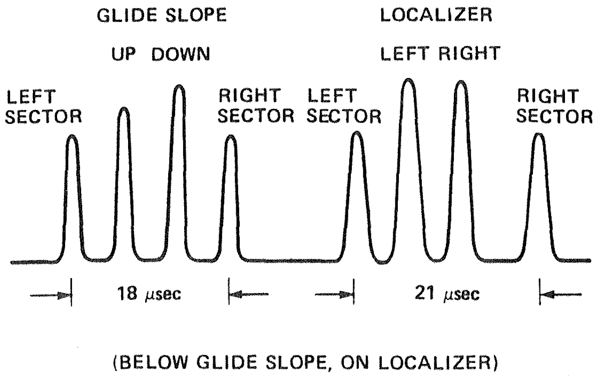

Fig. 7 Received beacon video signal aboard the aircraft.

Fig. 8 Sikorsky SH-3G flight-test helicopter.

Fig. 9 BLS flight demonstration on short final approach.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-86710		

4. Title and Subtitle	5. Report Date
DEVELOPMENT AND FLIGHT TEST OF A HELICOPTER, X-BAND, PORTABLE PRECISION LANDING SYSTEM CONCEPT	May 1985
	6. Performing Organization Code
7. Author(s) Thomas J. Davis and George R. Clary, and John P. Chisholm and Stanley L. Macdonald (Sierra Nevada Corp., Reno, Nevada)	8. Performing Organization Report No. 85187
	10. Work Unit No.
9. Performing Organization Name and Address NASA Ames Research Center Moffett Field, CA 94035	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code 505-42-41

15. Supplementary Notes

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16. Abstract

A beacon landing system (BLS), based on a novel, X-band, precision approach concept is being developed and flight tested as a part of NASA's Rotorcraft All-Weather Operations Research Program. The system is based on state-of-the-art X-band radar technology and digital processing techniques. The BLS airborne hardware consists of an X-band receiver and a small microprocessor, installed in conjunction with the aircraft instrument landing system (ILS) receiver. The microprocessor analyzes the X-band, BLS pulses and outputs ILS-compatible localizer and glide slope signals. Range information is obtained using an on-board weather/mapping radar in conjunction with the BLS. The ground station is an inexpensive, portable unit; it weighs less than 70 lb and can be quickly deployed at a landing site. Results from the flight-test program show that the BLS has a significant potential for providing rotorcraft with low-cost, precision instrument approach capability in remote areas.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Portable landing system Precision approach Radar beacon Beacon landing system Course softening	Unlimited Subject category - 04

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	13	A02

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